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Seismic and Volcanic hazards in Eritrea

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Abstract

The dramatic landscape of Eritrea is driven by large tectonic forces that are breaking apart the African continent. It lies at the northernmost extent of the East-Africa rift and due to these dynamic processes, volcanism and seismic activity are common in Eritrea. For example, in 1921 a local magnitude (M_L) 5.8 earthquake badly damaged the city of Massawa. The Dubbi Volcano erupted in 1861 resulting in over 100 fatalities and more recently, on the 12th June 2011, Nabro volcano in the southern Red Sea region of Eritrea erupted with little warning. Ash plumes shut down regional air traffic and, together with lava flows affected local populations (12,000 people were evacuated and there were 7 fatalities). Despite these obvious impacts, little is known about the volcanic or seismic hazards in Eritrea. A recent collaboration between the Eritrea Institute of Technology and three UK universities (University of Bristol, Birkbeck, University of London and University of Cambridge) aims to address this. In 2011 UK and Eritrean scientists deployed an array of broadband seismometers across the country. From these data, together with historical data from religious transcripts dating back to 1400 and other regional deployments in the Horn of Africa we have developed a catalogue of historical seismicity in Eritrea. The resulting hazard map indicates a band of elevated hazard on the plate boundaries and around Massawa, Gulf of Zula, and Bada. Secondly, through a detailed study of geological, geophysical and satellite observations we have detailed the recent eruption of Nabro. This has led to an understanding of the volcano's behaviour, which can be related to the six other unmonitored volcanoes in Eritrea. In the future it is hoped that our collaboration will lead to the establishment of a permanent seismic network in the country. This is important for academic research (understanding rifting in East-Africa), humanitarian needs (e.g., monitoring and hazard assessment), as well as for large infrastructure projects such as geothermal power (e.g., Alid), mining (e.g., Potash) and other infrastructure (e.g., ports around Tio and Massawa) within the active rift zones.

1. Introduction

The East African Rift System (EARS) is a classic example of a continental rift and Eritrea is located at the northernmost extent of this rift system (Figure 1). Eritrea hosts the final stages of the rifting process and thus, it is prone to earthquakes and volcanic eruptions synonymous with the rifting process. Despite these geological and geophysical phenomena little is known on the recurrence of earthquakes, seismic and volcanic hazards in Eritrea. In addition, given the rapid development within Eritrea with big infrastructure projects planned around Massawa and Bada it is timely to understand the impacts of earthquakes and volcanism in Eritrea. In this paper we outline recent UK-Eritrea collaborations aimed at understanding these hazards in more detail.

2. Tectonic setting

The tectonics of Eritrea is governed by the divergence of the three plates – the Arabia, Nubia and Somalia plates, which meet at the Afar triple junction (Figure 1). The Red Sea Rift (RSR) formed by the separation of the Arabia and Africa (Nubia) plates in Early Miocene (Steckler et al., 1988; McClusky et al., 2003). The EARS marks the boundary between the Nubia plate to the west and the Somalia plate to the east, both plates are part of what was formerly known as African plate (Chu and Gordon, 1998). The separation of the Arabia from the Somalia plate formed the Gulf of Aden (GA) in Djibouti (Figure 1). It has been shown from seismic studies and supported by our current seismicity map that there is a microplate known as the Danakil microplate which is surrounded by the RSR, GA and the Nubia plate (Chu and Gordon, 1998; Figure 2). There are four main physiographic units in Eritrea associated with tectonic structures known as the plateau, the rift margin, the Red Sea rift and the Afar rift (Figure 1).

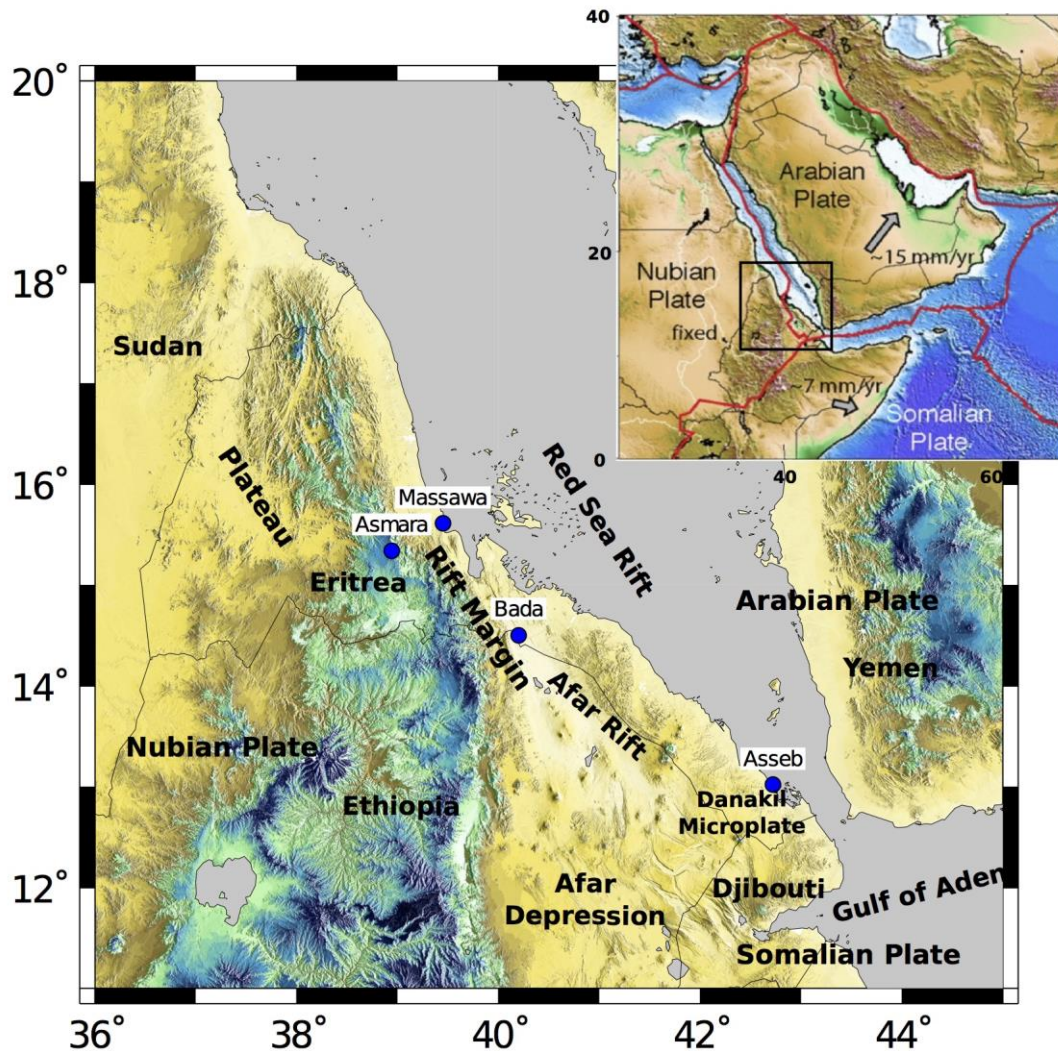


Figure 1. Location and Tectonic map of Eritrea and surrounding. Blue circles show the location of the capital city (Asmara) and some cities and towns in east and southeast Eritrea. Inset map shows NE Africa and Arabia (Keir et al., 2013). Arrows show plate motions relative to the Nubian Plate. Red lines show the major plate boundaries.

3. Where do earthquakes occur in Eritrea?

Gouin (1979), through analysis of religious, historical records and newspapers compiled historic earthquakes in the horn of Africa. From this, the earliest recorded earthquake in the region was in 1400 around Dubbi volcano. Since then a number of earthquakes have been recorded in Eritrea and we have compiled a catalogue from different sources including:

- The book of Gouin (1979) covering the time span of 1400-1964 for the historic events.
- The reviewed version of the International Seismological Centre (ISC) catalogue that covers earthquakes from 1964-2012.
- A local Eritrean catalogue that was maintained by the University of Asmara and Eritrea Institute of Technology for the period of 1999-2004.
- A regional catalogue from Eastern and Southern Africa Regional Seismological Working Group (ESARSWG) for the duration 1993-2012.
- The dataset that we located from six regional stations that have been deployed in June 2011 (indicated as Eri Regional in Figure 2).

The assembled catalogue consists of 5896 earthquakes for the duration 1400 to the present and within latitudes 12° to 20° and longitudes 36° to 44° (Figure 2).

In 1884 Massawa was severely damaged by an earthquake of magnitude 5.9 and later, earthquakes in 1912, 1913 and 1921 that reach a magnitude of 5.8 (Gouin, 1979; Ogubazghi and Woldehaimanot, 1998). More recently, swarms of earthquakes occurred in Massawa in 2002 with the largest, magnitude 4.4 (Ogubazghi, 2002). Tremors of earthquakes also occur around the city of Keren in 1875 and 1876 (Gouin, 1979). These earthquakes are likely the result of movement on large border faults marking the edge of the rift zone.

Starting in May 1993 a series of earthquakes occurred around Bada, Southeastern Eritrea with magnitudes ranging from 4.2 to 5.2 (Ogubazghi et al., 2004; Ogubazghi and Goitom, 2015). The large number of similarly sized magnitudes led Ogubazghi et al., (2004) to suggest this was related to the injection of magma into the crust, a phenomenon commonly seen within the volcanically active Afar Depression to the south (Wright et al., 2012).

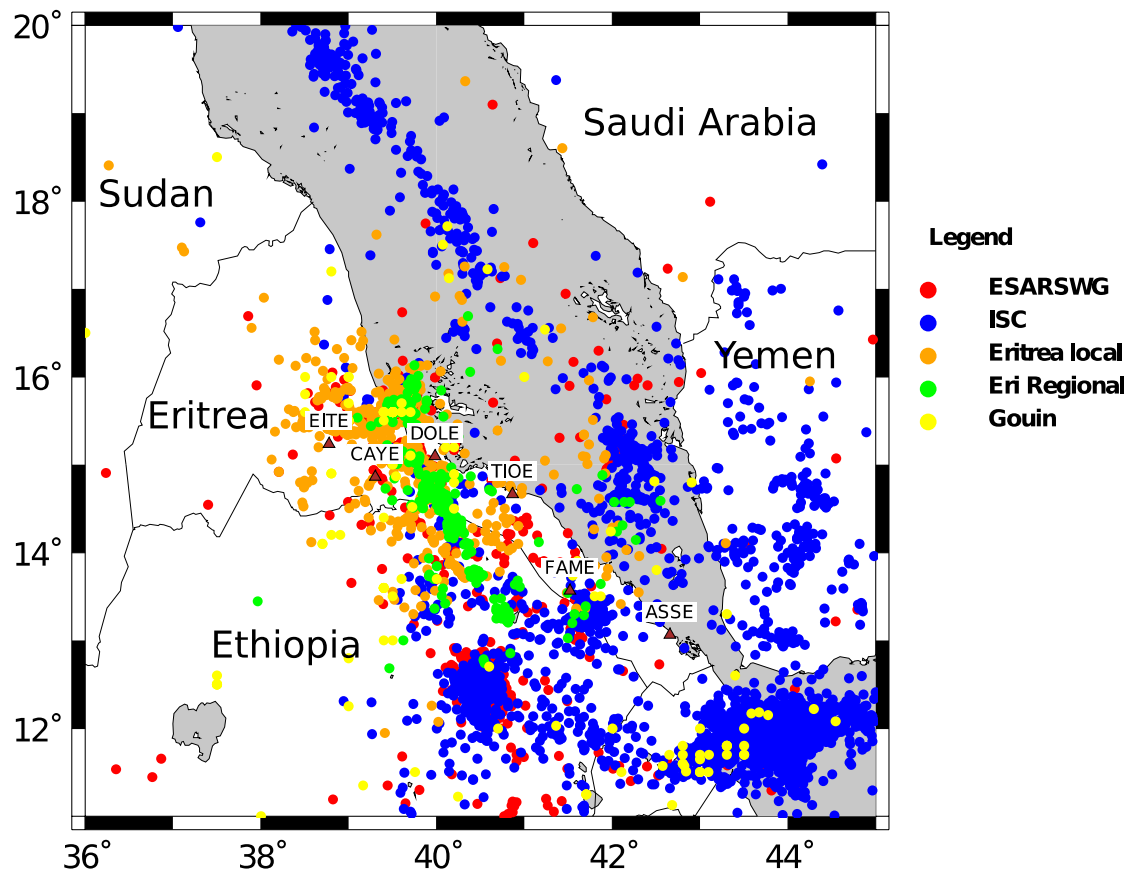


Figure 2. Seismicity of Eritrea from 1400 to present. Each circle shows an earthquake epicentre. Legend indicates different source catalogues. (See text for more discussion). Triangles show the stations deployed in June 2011. EITE, the station deployed at Eritrea Institute of Technology, CAYE, at Adi Keyih, DOLE, at Bordele, TIOE, at Tio, FAME, at Afambo, and ASSE, at Asseb.

Other significant earthquakes are directly linked with volcanic activity. The 1400 earthquake around Dubbi was accompanied by a volcanic explosion and was reported by sailors on the Red Sea. Moreover in 1861 an earthquake of magnitude 5.5 associated with the Dubbi volcano was also recorded (Gouin, 1979). In 1901 and 1902 a series of earthquakes were reported around Alid volcano. Recently in March 2011 an earthquake of magnitude 4.8 was recorded around Siroru, which preceded the Nabro eruption by roughly 3 months. On June 12, 2011 swarms of earthquakes were recorded globally about 5 hours before the eruption and continue for months after the eruption (Goitom et al., 2015).

Table 1. Some of the historic and recent earthquakes within Eritrea

YY-MM-DD	Latitude	Longitude	Magnitude *	Locality
1400-00-00	13.50	41.87	6.0 (M_E)	Dubbi
1861-05-08	13.74	41.55	5.5 (M_L)	Dubbi
1875-11-02	16.0	38.5	6.0 (M_L)	Keren
1884-07-20	15.7	39.6	5.9 (M_S)	Massawa
1902-01-00	15.1	39.7	5.0 (M_E)	Alid

1913-02-18	15.5	39.0		Massawa
1921-08-14	15.6	39.5	5.8 (M _S)	Massawa
1993-05-06	14.40	40.13	5.3 (M _L)	Bada
2002-07-13	15.73	39.55	4.4 (M _L)	Massawa
2011-03-31	13.35	41.69	4.8 (M _L)	Siroru
2011-06-12	13.46	41.67	5.8 (M _L)	Nabro

* Magnitude types: (M_E) = Non-instrumental, (M_L) = Local, (M_S) = Surface-wave

4. Where do volcanoes occur in Eritrea?

In Eritrea volcanoes are identified in the eastern and southeastern parts of the country along two major axes, NNW-SSE and NNE-SSW. There are seven volcanic centres in Eritrea; Alid, Jalua, Dubbi, Mabda, Nabro, Asseb and Gufa volcanic fields (Figure 3). Alid and Jalua volcanoes are found between Gulf of Zula and Bada along NNW-SSE trend and are extensions of the East African Rift volcanoes. There is no recorded eruptive history of these volcanoes, but a number of recent eruptions have occurred from volcanoes on the same trend in the Afar Depression to the south in Ethiopia (e.g., Dalafilla (Field et al., 2012), Erte Ale (Pagli et al., 2012)) and to the north in the Red Sea (Jabel al Tair (Marchese et al., 2009), Zubair (Barnie et al., 2016)). The volcanism of the Area has previously been studied by various scholars decades ago (e.g. Barberi et al., 1972; Barberi and Varet, 1977).

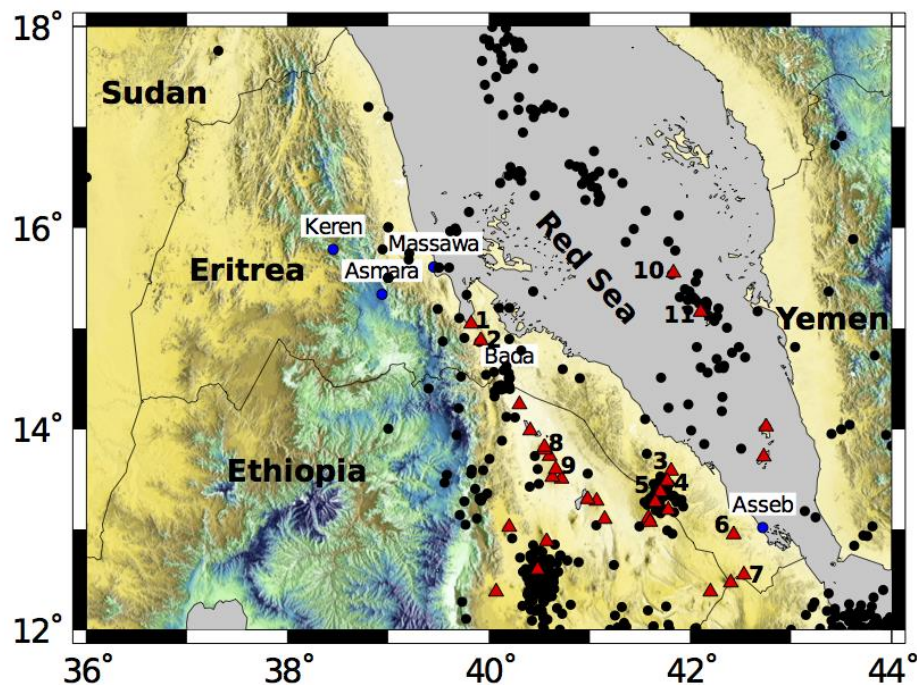


Figure 3. Volcanic centres in Eritrea and surrounding. Red triangles show major volcanoes. 1=Jalua, 2=Alid, 3=Dubbi, 4=Mabda, 5=Nabro, 6=Asseb 7=Gufa, 8=Dalafilla, 9=Erte Ale, 10=Al Tair and 11=Zubair. The black dots are earthquakes M>4.5 during 1400-2012

In the Southern Red Sea region a number of volcanoes are found on a NNE-SSW trend. The most prominent of these are Dubbi, Mabda and Nabro. Dubbi erupted in May 1861 and in 2000 was reported as the largest volcanic eruption in the history of African volcanism (Wiert and Oppenheimer, 2000). It resulted in several lava flows that travelled for roughly 22 Km towards the Red Sea and dramatic pyroclastic flows (fast moving hot clouds of ash and rock) that claimed the lives of more than 100 people and buried villages (Wiert and Oppenheimer, 2000). Maritime traffic in the Red Sea was interrupted due to this eruption (Wiert and Oppenheimer, 2000).

The most recent volcanic eruption recorded in Eritrea is that of Nabro volcano. Nabro volcano, which is located 25 km southwest of Dubbi volcano, erupted explosively around 20:30 GMT on June 12, 2011. It erupted with very little warning following ~5 hours of seismic activity. The SO₂ released to the atmosphere was estimated around 4.5 Tg within 15 days of the eruption (Theys et al., 2013) and is believed to be the biggest amount emitted since the 1991 Pinatubo eruption in the Philippines. Air traffic was disrupted for some days in the region. Several lava flows emerged from the vent with the largest travelling roughly 17.5 Km towards the SW (Figure 4). Goitom et al. (2015) have used seismological, satellite remote sensing, infrasound data and brief field surveys to study the synthesis and evolution of the eruption. They explained that (i) Nabro was seismically quiet before its eruption, (ii) the eruption was associated with a shallow dike intrusion orienting NW-SE, (iii) the eruption resulted in huge amount of SO₂, and (iv) the onset of the eruption was marked by high seismicity, high SO₂ and high infrasound. Due to rapid evacuation of the people from the calderas casualties were minimised, but 7 people lost their lives and roughly 12,000 people have been displaced (Solomon, 2012).

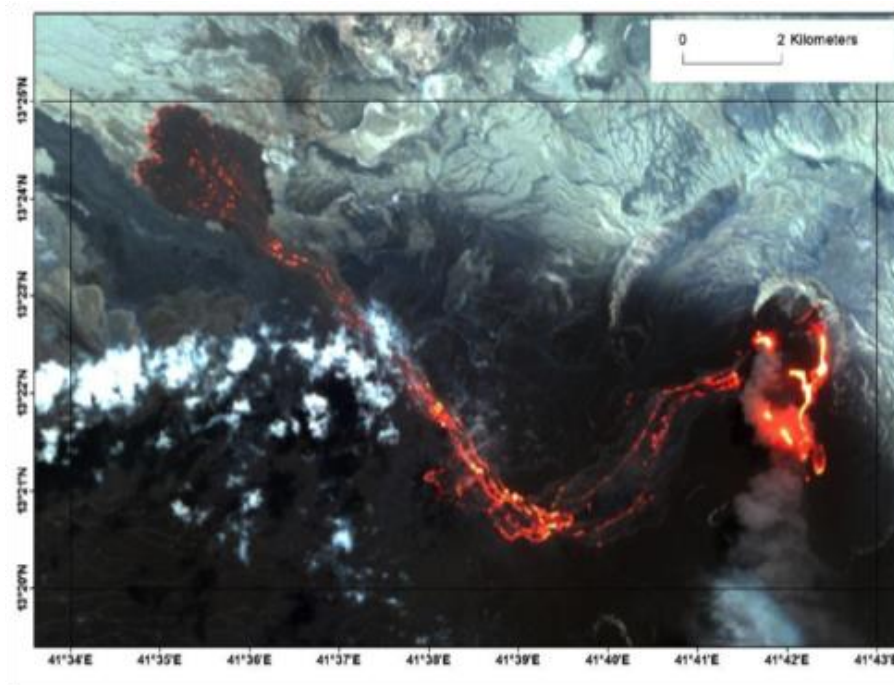


Figure 4. Satellite image of the lava flow from the Nabro vent in June 2011.

Figure 4. Satellite image of the lava flow from the Nabro vent in June 2011

The Asseb and Gufa volcanic fields are found in the southeastern part of Eritrea close to the Djibouti border and are basaltic cinders associated with massive lava flows. Both of them trend in an E-W direction towards the Red Sea.

5. Collaboration of UK Universities with EIT

The first memorandum of understanding (MOU) for a geophysical collaboration work was signed between Eritrea Institute of Technology (EIT) and the University of Bristol (UOB) in April 2011. Following this, in June 2011 EIT, UOB, Birkbeck, University of London and University of Cambridge deployed six broadband seismic stations (Figure 5 and 6) in the central and eastern parts of Eritrea to study the crustal and mantle structure in the Horn of Africa (e.g., Hammond et al., 2013, Civiero et al., 2015). These temporary stations remain in site until October 2012 and recorded data for about 16 months.

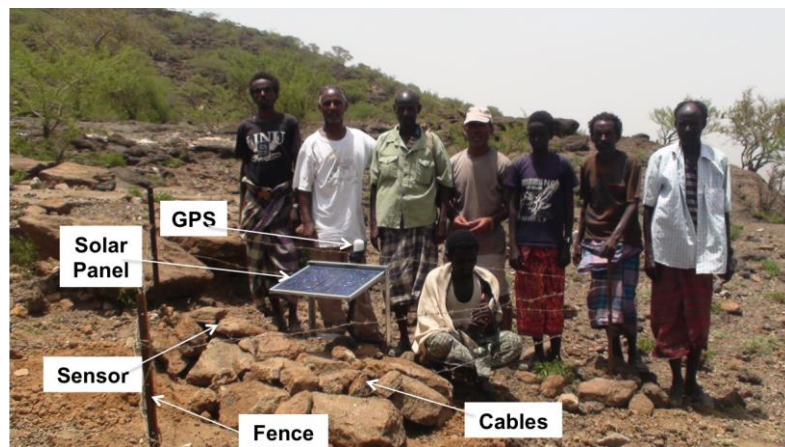


Figure 5. A seismic station setup on Nabro.

After the Nabro eruption an urgent project was funded by the Natural Environmental Research Council (NERC) for rapid deployment of 8 broadband seismic stations in August 2011 to monitor on-going earthquake activity (Figure 6). These stations (except one, which flooded) recorded high quality data for about 15 months until they were decommissioned in October 2012.

The data from both Eritrea network (shown on Figure 2), and Nabro network (shown on Figure 6) have been analysed and the results published in international journals (e.g. Hammond et al., 2013, Hamlyn et al., 2014; Goitom et al., 2015, Civiero et al., 2015) and work is on-going to develop seismic and volcanic hazard assessment of Eritrea (Goitom et al., 2017 in press).

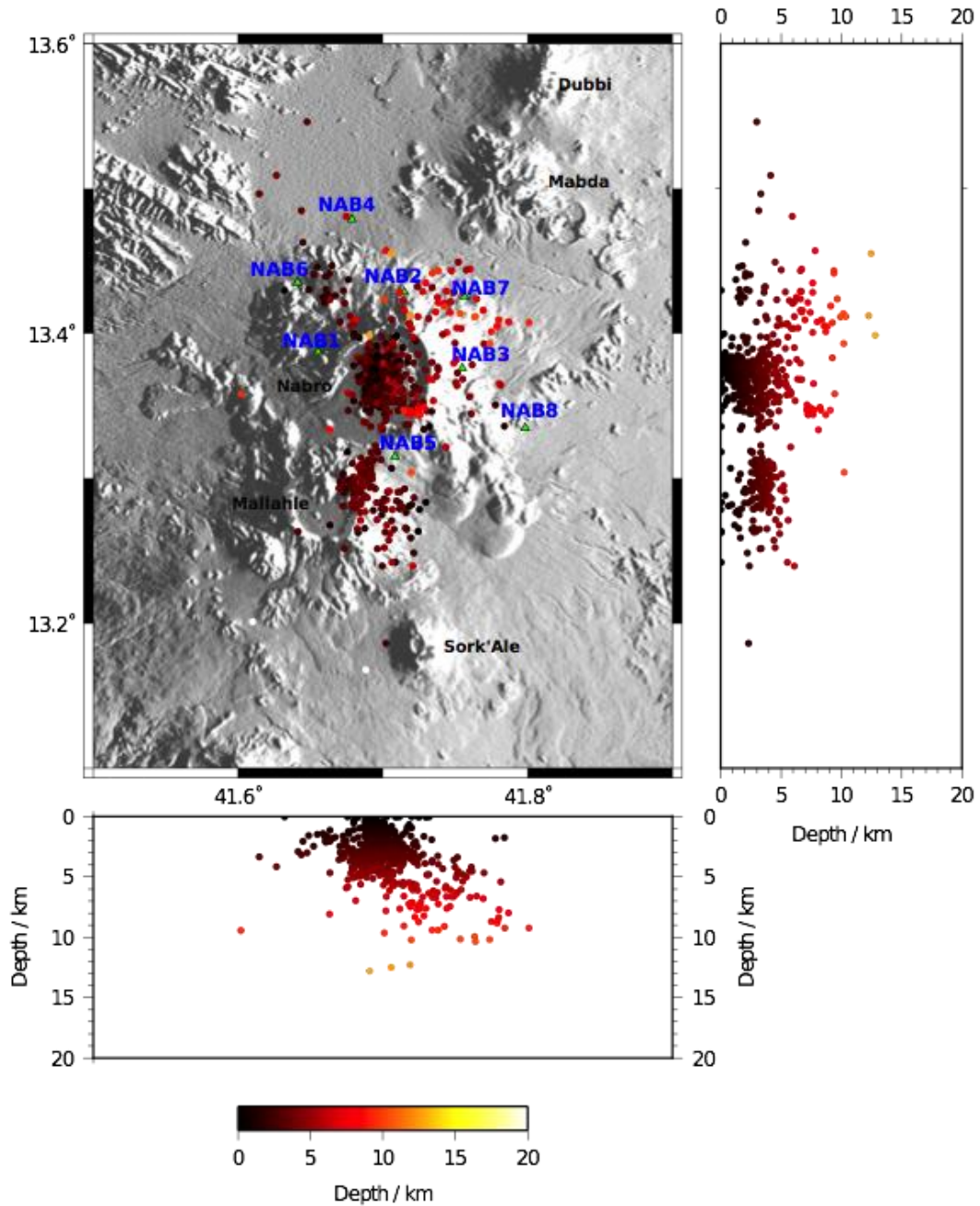


Figure 6. Location of the eight seismic stations deployed around Nabro in August 2011. Included is the seismicity of Nabro in about one month (August 30 to October 8, 2011) modified after Hamlyn, 2014. During this period 658 events have been located with local magnitudes ranging from 0.3 to 4.5.

6. Conclusion and Recommendations

It is clear that Eritrea is susceptible to damaging earthquakes (e.g. Massawa and Bada) and big volcanic eruptions (e.g. Dubbi and Nabro). However, cyclicity of the earthquakes is not well understood. Eritrea is a country aiming towards rapid economic development with significant infrastructure projects planned (e.g., geothermal energy, mining, port development). As a result, there

is a pressing need to understand these hazards in more detail. However, currently there is no earthquake or volcano monitoring in Eritrea. Recent guidelines suggest that every volcano at risk of eruption should ideally have a seismic network, or at minimum one seismometer transmitting data real time to a dedicated observatory (Sparks et al., 2012). Similarly, an Eritrean wide seismic network would allow better characterisation of seismic hazards and facilitate mitigation strategies for future earthquakes. International and regional collaborations, such as that outlined here, offer a way to develop this capacity within Eritrea. Importantly, the existing Eritrean-UK collaboration includes training of an Eritrean scientist in seismic and volcanic hazards. This combination of investment in equipment and skills represents the most effective way of building a sustainable geophysical observatory in Eritrea capable of guiding policies on seismic and volcanic hazards.

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